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Real-Time Modeling of Gas-Electric Dependencies: An Optimal Control Approach

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Real-Time Modeling of Gas-Electric Dependencies: An Optimal Control Approach

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Abstract

In this thesis, several turbine-governor models such as GAST model and GGOV1 model are implemented. The simulation of the models takes electric power and speed as the variable input, respectively, to see what will influence the fuel consumption and mechanical power. These two models are implemented in detail and incorporated with non-windup limiters. Different implementations for the non-windup limiters are considered and compared. In addition to the single gas turbine model, its integration to a power system model is developed as well. We consider two-area systems, one with simple primary speed droop control and one with supplementary automatic generation control.

Chapter 1

Introduction

1.1 Gas Turbine

Gas turbine plays an important role in power systems, which takes the duty of converting natural energy into electricity. Usually a gas turbine consists of three or four parts, a gas compressor, a turbine on the shaft and a combustor, and with a fourth component-electric generator, the energy can be converted into electric form.

Firstly, the air will be compressed within the compressor. Fuel will be then mixed with the compressed air and burnt in the combustor. After which, the exhausted gas flow rotate the blades of the turbine and consequently the shaft of the generator connected to it.

In turbine-governor model, the governor model with given speed reference(SPEED ref) determines gate value(GATE) for the turbine model, and turbine model determines the mechanical power(Pmech) or torque for the generator model.

Turbine-Governor models like GAST model, Rowens model, GGOV1 model are commonly used in research.

1.2 PID controller

Power systems tend to be unstable under severe load disturbance. Severe disturbances can trigger a plant shutdown. Therefore, a lot of controllers are designed to maintain system stability.

PID controller [2] offers continuously modulated control to a power system. The overall control function can be expressed as:

$$u(t) = K_{\mathrm{p}} e(t) + K_{\mathrm{i}} \int_0^t e(t')\, dt' + K_{\mathrm{d}} \frac{de(t)}{dt}, \tag{1.1}$$

It consists of three parts, proportional term, integral term and derivative term, $e(t)$ is the error, the proportional term gives the directly correction, the integral term makes up the cumulated error, and the proportional term was for possible future error.

The proportional term K_p will decrease rise time but also lead to oscillatory performance. The derivative control K_d reduces the oscillations by providing proper damping but may be detrimental to transient performance and stability. The K_i integral control considers the cumulated error and reduces the steady-state error to zero. The primary design goal is to obtain a good load disturbance response by optimally selecting PID controller parameters. Tuning of PID controller coefficients can be made by heuristic algorithm such as genetic algorithm [3], bat algorithm [5] and partial swarm algorithm [6].

1.3 Hierarchical control

The generation of power units and consumption of loads connected needs to be controlled and monitored. Hierarchical control consists of three control levels, each with different characteristics and qualities, and all depending on each other [11]:

Level 1 (Primary control): The primary control monitor the normal operation to keep the balance between generation and consumption. Droop control method is one of the methods normally used as a primary control method in modeling. In this level, the control loops of all generating units respond almost within a few seconds.

Level 2 (Secondary control): The objective of secondary control is keeping the balance between generation and consumption within each control area based on secondary control reserve. In this level, centralized and continuous automatic generation control is chosen to balance the load after an incident, usually in the time-frame of seconds up to typically 15 minutes.

Level 3 (Tertiary control): Similar to secondary control, tertiary control works based on secondary reserves as well. It is mainly used to release secondary reserves in a balanced system, but sometimes also used as a supplementary method to restore system frequencies after large incidents. At this level, the balance of power will be taken into consideration.

The power system control problem can be regarded as a optimization problem which involves random process and stochastic control in continuous time.

Chapter 2

GAST Model

In gas turbine energy is converted into power. The GAST model [9] is one of the most commonly used models, which consists of two parts, the generator and the gas turbine. In this thesis, we will use this model as the main research entity. The implementation and parameters will be presented in this chapter. The block diagram is shown in Figure 2.1:

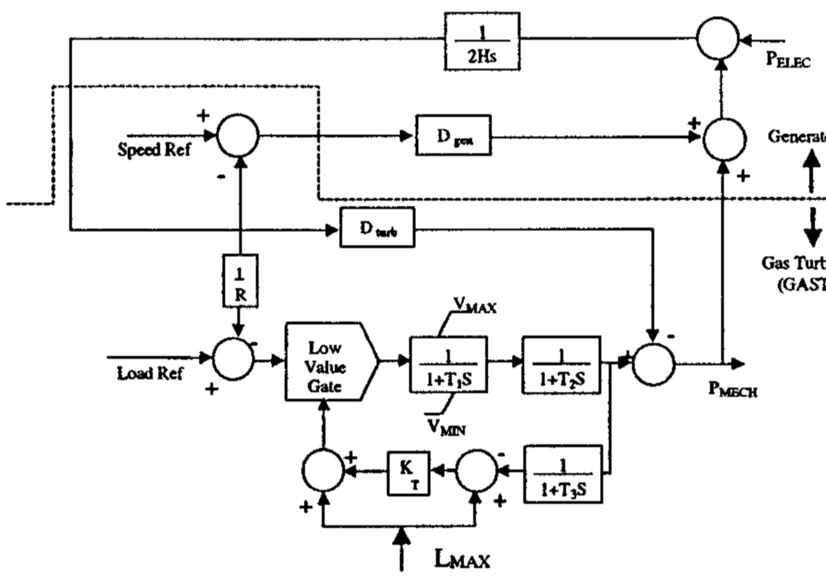

Figure 2.1: The GAST model to represent dynamic behavior of the gas governor-turbine [9]

2.1 Simulation of GAST Model

Figure 2.1 shows the GAST model which was one of the most commonly used dynamic models [9] due to its simplicity. The block with the bounds Vmin, Vmax has limits on the output. The bounds should be implemented in a way that prevents windup, i.e., in a way that prevents the growth of the integral error term when the output. But simulations found online usually regard the non-windup limiters as saturation, in this thesis the non-windup limiters will be implemented step by step in detail.

The GAST model can be implemented as shown in Figure 2.2. The subsystem called non-windup includes the lag function with non-windup limits block diagram as shown in Figure 2.3.

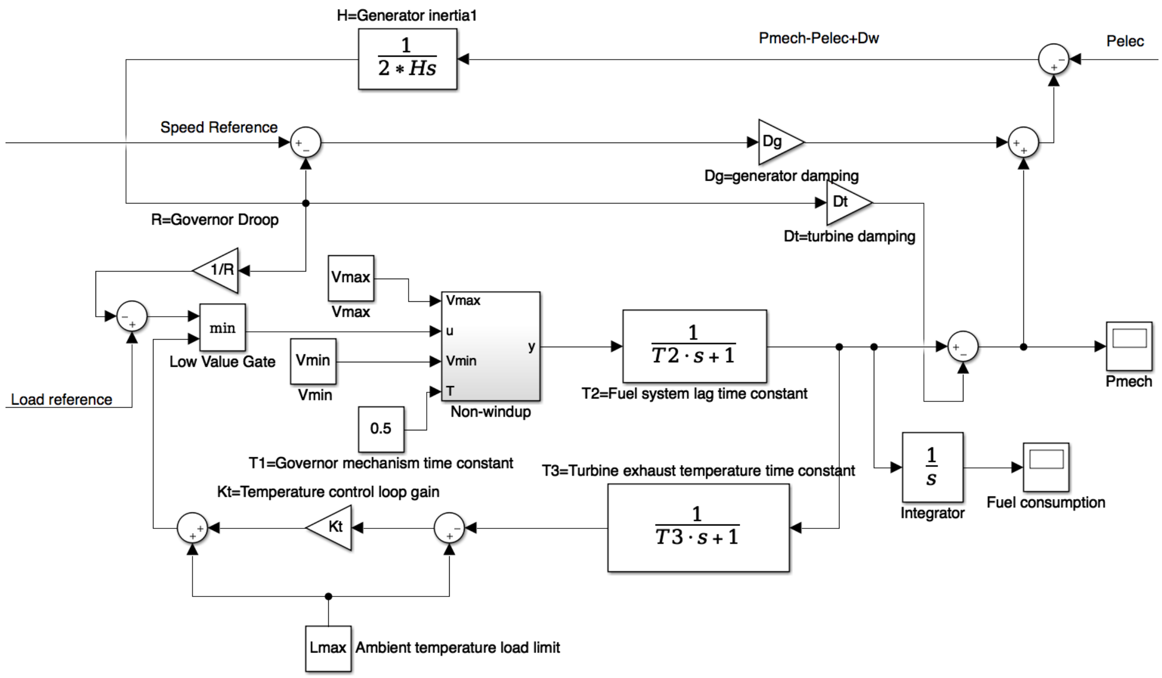

Figure 2.2: Simulation of GAST model

The Pelec and fuel flow are shown in Figure 2.4 and Figure 2.6

The machine speed and power relationship is given by swing equation:

$$2H\frac{d\omega}{dt} = (Pmech - Pelec) + D\omega, \tag{2.1}$$

The valve position controlled by the non-windup subsystem is limited by the given speed and

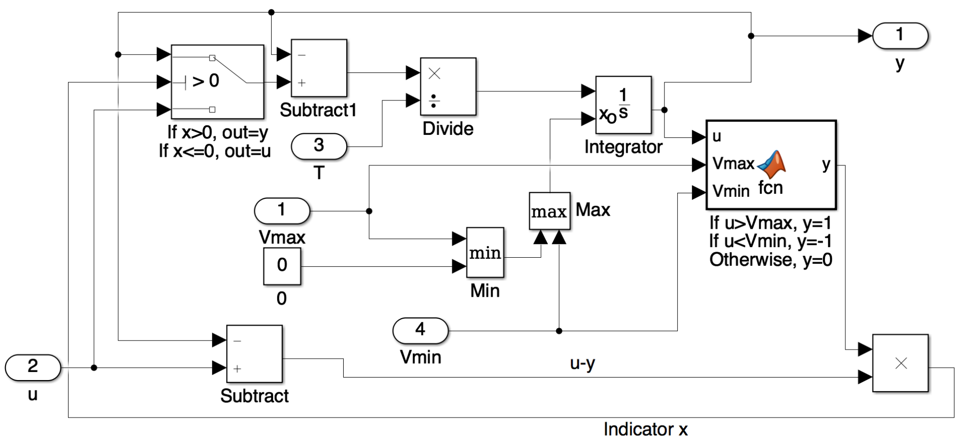

Figure 2.3: Non-windup subsystem

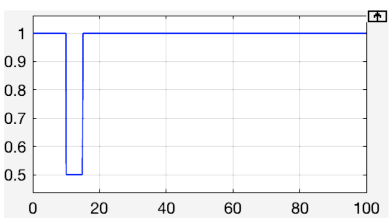

Figure 2.4: PELEC

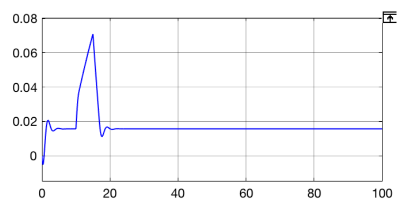

Figure 2.5: $\Delta\omega$

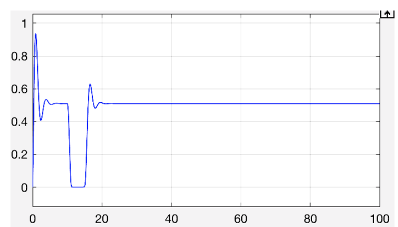

Figure 2.6: Fuel flow

exhausted temperature, and controls the fuel flow. The temperature, however, is influenced by both air flow and the fuel flow. The mechanical power(Pmech) is the output of the turbine, to which the input of the generator is connected. The droop control in this model balances the generation and load.

In our simulation, we vary the electric power to see the response to a sudden variation of electric load. As shown in Figure 2.4, Figure 2.5 and Figure 2.6, the decrease of Pelec gives rotor a speed up. The fuel flow drop afterwards. when the power demand suddenly drops to 0.5pu, the fuel flow drop as well.

2.2 Non-Windup Limit

The transfer functions with non-windup limits are not readily available in Simulink. There are three types of non-windup blocks: integrator with non-windup limits, single time constant block with non-windup limits, lead-lag function with non-windup limits. The single time constant block

Parameter	Representation	Value[9]	Range[1]
R	Governor Droop	0.032	(0,1)
T1	Fuel valve time constant	0.4	(0.04,0.5)
T2	Fuel system lag time constant	0.1	(0.04,0.5)
T3	Turbine exhaust temperature time constant	3	(0.04,5.0)
Lmax	Ambient temperature load limit	1	NA
Kt	Temperature control loop gain	1	(0,5)
Vmax	Maximum valve position	1	(0.5,1.2)
Vmin	Minimum valve position	0	(0,1.0)
Dt	Turbine damping factor	0.15	(0,0.5)
Dg	Generator damping factor	0.5	NA

Table 2.1: GAST Parameter

with non-windup limits is in the GAST model and thus need to be implemented in Simulink.

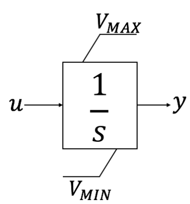

Figure 2.7: integrator with non-windup limits

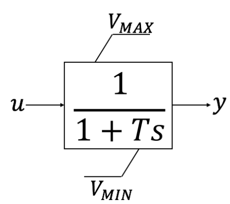

Figure 2.8: single time constant block with non-windup limits

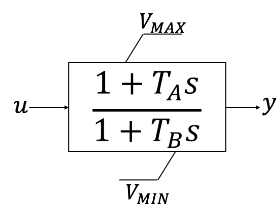

Figure 2.9: lead-lag function with non-windup limits

If the integrator with non-windup limiter can be successfully implemented, the method may offer some inspiration for the implementation of the remaining two. The integral non-windup operation is defined in [7], page 359, as follows:

The system equation is: $f = u$

The limiting action is: If $Vmin < y < Vmax$, then $dy/dt = f$

If $y >= Vmax$ and $f > 0$, then set $dy/dt = 0, y = Vmax$

If $y <= Vmin$ and $f < 0$, then set $dy/dt = 0, y = Vmin$

Set Vmax=-0.025, Vmin=-0.25

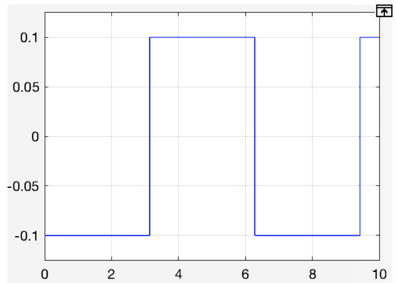

Figure 2.10: Input signal

Several methods have been tried. The first method is to subtract the input signal when the output touches the bound, the block diagram is shown in Figure 2.11:

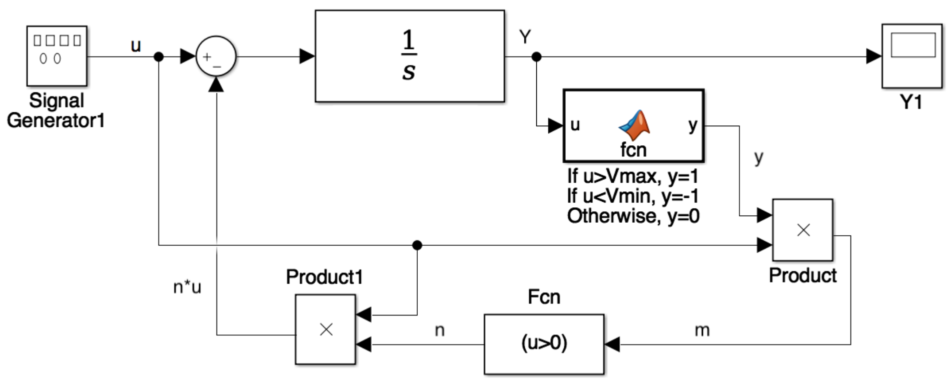

Figure 2.11: Integrator with non-windup limits (version 1)

In Simulink, all the input data will be set as u, so here the indicators are set over the real line. When Y is greater than Vmax, y equals to one, and if u is greater than zero, the product m will be positive, and n will equal to one, then n times u to be subtracted by u, the input signal will be offset to zero. If Y is less than Vmin and u is less than 0, the signal will be offset in the same way.

Figure 2.12 shows that the initial point can be out of bound and the line does not strictly lay between the bounds, it has little fluctuation in area near the bounds. As the given input signal and the constraints, the gradient k is in set(-0.1, 0.1, 0). But in Figure 2.12 above, in the area near the bounds, the line becomes smooth. The second method multiplies the signal with zero when it touches the bounds.

The block diagram is shown in Figure 2.14. When Y is greater than Vmax, y equals to one,

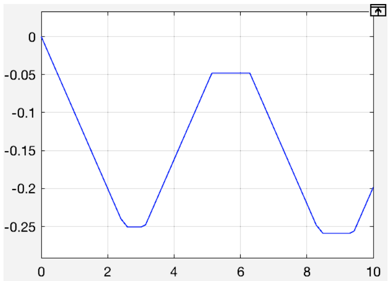

Figure 2.12: Output signal (version 1)

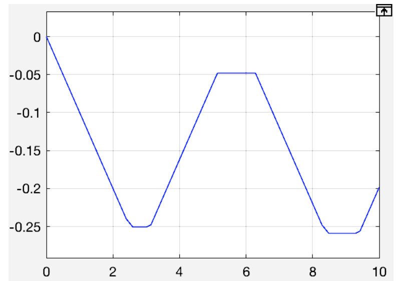

Figure 2.13: Output signal (version 2)

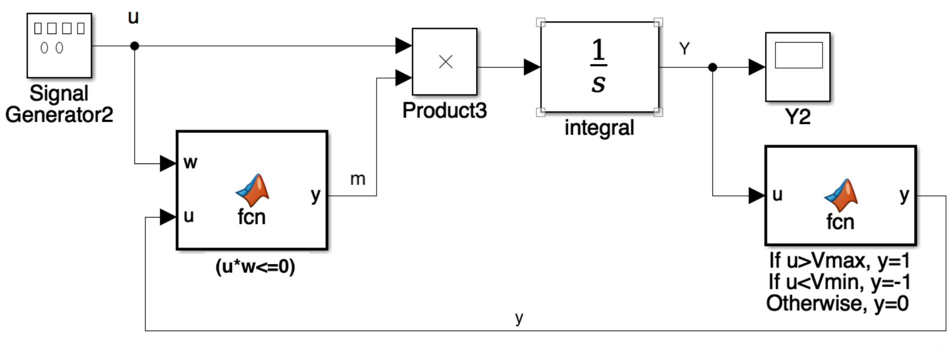

Figure 2.14: Integrator with non-windup limits (version 2)

and if u is greater than zero, the indicator m will be zero, then the input signal u will be multiplied by m and become zero. If Y is less than Vmin and u is less than 0, the signal will be processed in the same way. The output is shown in Figure 2.13, which is exactly the same as Figure 2.12.

In third method, we do not try to control the input signal by subtraction or multiplication, but switch the signal to zero when the bound is reached. The block diagram is shown in Figure 2.15:

The initial point of Y is zero, and in this diagram the initial point will be checked and modified if zero is out of the bound. After that, when Y is greater than Vmax, y equals to one, and if u is greater than zero, the product m will be positive, then the input signal will be switched to zero. If Y is less than Vmin and u is less than 0, the signal will be processed in the same way. The input and output is shown in Figure 2.16 and Figure 2.17:

This method gives perfect output, there is no smoothing line near the bound and the output is strictly bounded.

The simple time constant non-windup limiter needed in GAST model, is defined as follows [7],

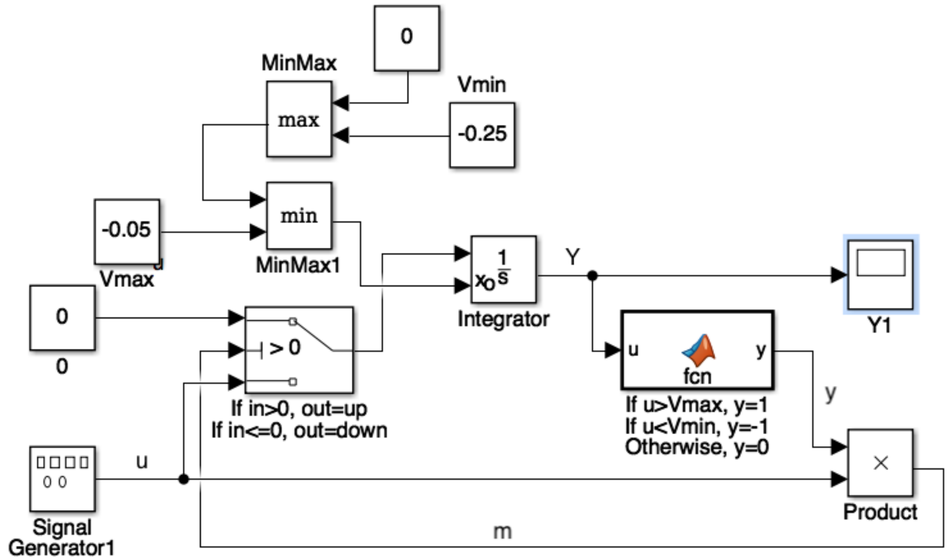

Figure 2.15: integrator with non-windup limits (version 3)

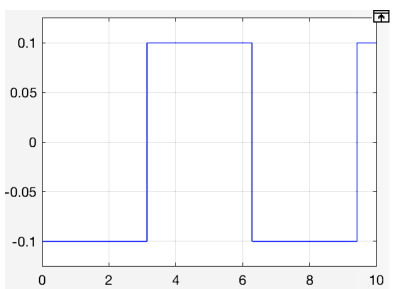

Figure 2.16: Input signal (version 3)

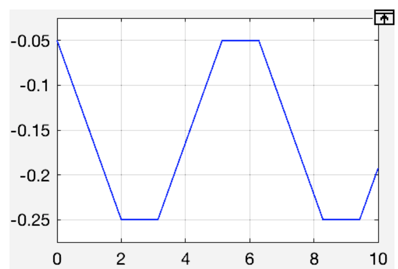

Figure 2.17: Output signal (version 3)

page 360.

The system equation is: $f = \frac{u-y}{T}$

The limiting action is: If $Vmin < y < Vmax$, then $dy/dt = f$

$$\text{If } y >= Vmax \text{ and } f > 0, \text{ then set } dy/dt = 0, y = Vmax$$

$$\text{If } y <= Vmin \text{ and } f < 0, \text{ then set } dy/dt = 0, y = Vmin$$

Set T=10, Vmax=0.8, Vmin=0.2. The block diagram is drawn by the same method from the integrator with non-windup limits.

In the block diagram shown in Figure 2.18, when y touches the upper bound Vmax, m equals to one, and if u-y is greater than zero, the product x will be positive, then the input signal will be switched to y, and in this transfer function, f equals to (u-y)/T, when u equals to y, the output

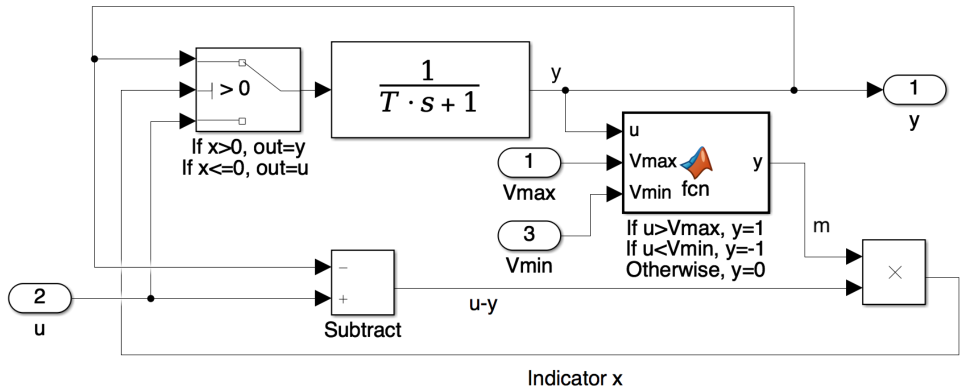

Figure 2.18: single time constant function with non-windup limits (version 1)

will be static. When Y is less than Vmin and u is less than y, the signal will be processed in the same way.

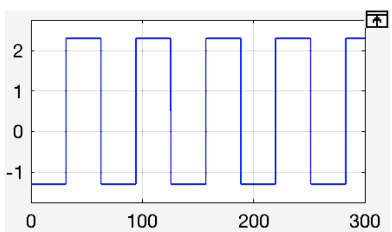

Figure 2.19: Input signal (version 1)

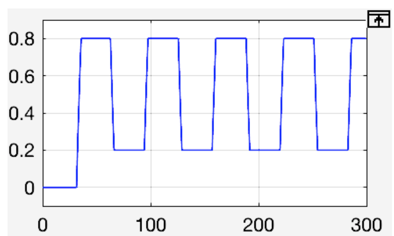

Figure 2.20: Output signal (version 1)

The input signal and output signal is shown in Figure 2.19 and Figure 2.20. According to the figures above, we know that this method works well except setting initial point. In next step, we will explore the method can bound the initial point.

After making some efforts, we found that the transfer function is unable to set the initial point in this case, so we use several blocks to represent the transfer function and follow the definition. The initial point issue was addressed as in integrator with a nonzero initial condition. The block diagram is shown in Figure 2.3:

Due to the property of the single time constant lag transfer function, and the definition of the non-windup limiter, the input signal will be switched to y if the signal is greater than u when y touches the upper bound in the block diagram shown in Figure 2.21. Besides, the initial points zero will be tested either in the bound or not, if zero is greater than the upper bound, the initial

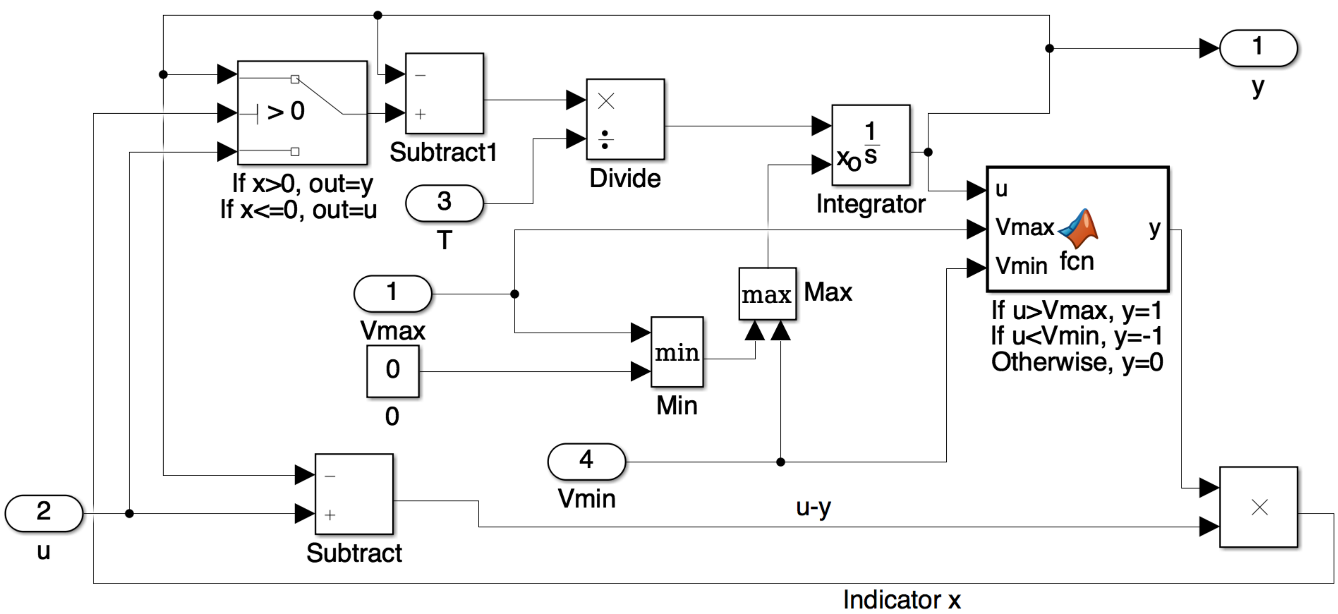

Figure 2.21: single time constant lag function with non-windup limits (version 2)

point will be the Vmax in this instance, or Vmin when zero is less than the lower bound. The input and output signal is shown in Figure 2.22 and Figure 2.23:

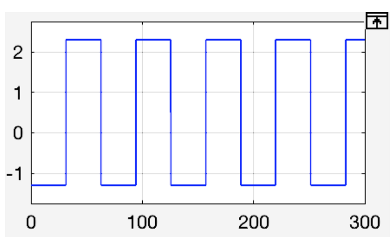

Figure 2.22: Input signal

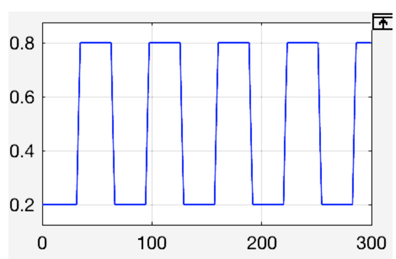

Figure 2.23: output signal

This method can implement the non-windup operation perfectly. In next chapter, this non-windup limiter blocks will be incorporated in GAST model and GGOV1 model, which is one of the simplest turbine-governor models and one of the more recent models.

Chapter 3

GGOV1 Governor-Turbine System

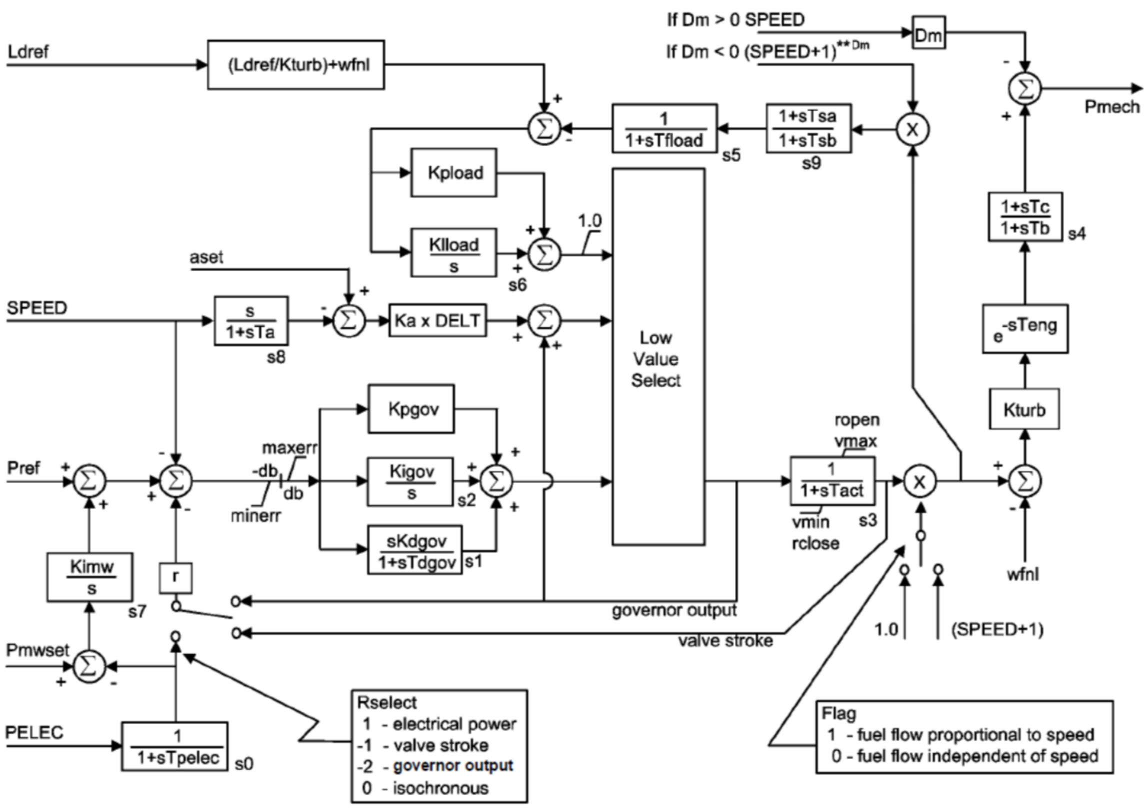

Figure 3.1: GGOV1 [1]

The GAST model is not recommended because it only considers simple droop control, constant load limitation, and the fuel valve response, turbine response, and load limit response using three time constants. More recent digital model usually considers a PI or PID controller, which is not able to be fully represented in the GAST model implemented in last chapter.

Nowadays, GGOV1 model, studied in [8] [10], is one of the leading models to represent gas turbines with various controls. As shown in Figure 3.1, various controls are presented in blocks in this model: valve position and actuation, fuel system dynamics, load limiter for exhaust temperature controls, load controller for plant-level or outer loop controls, acceleration limiter and governor deadband. In this chapter, the GGOV1 model is implemented in detail, with the table of parameters of GE gas turbine obtained from [4].

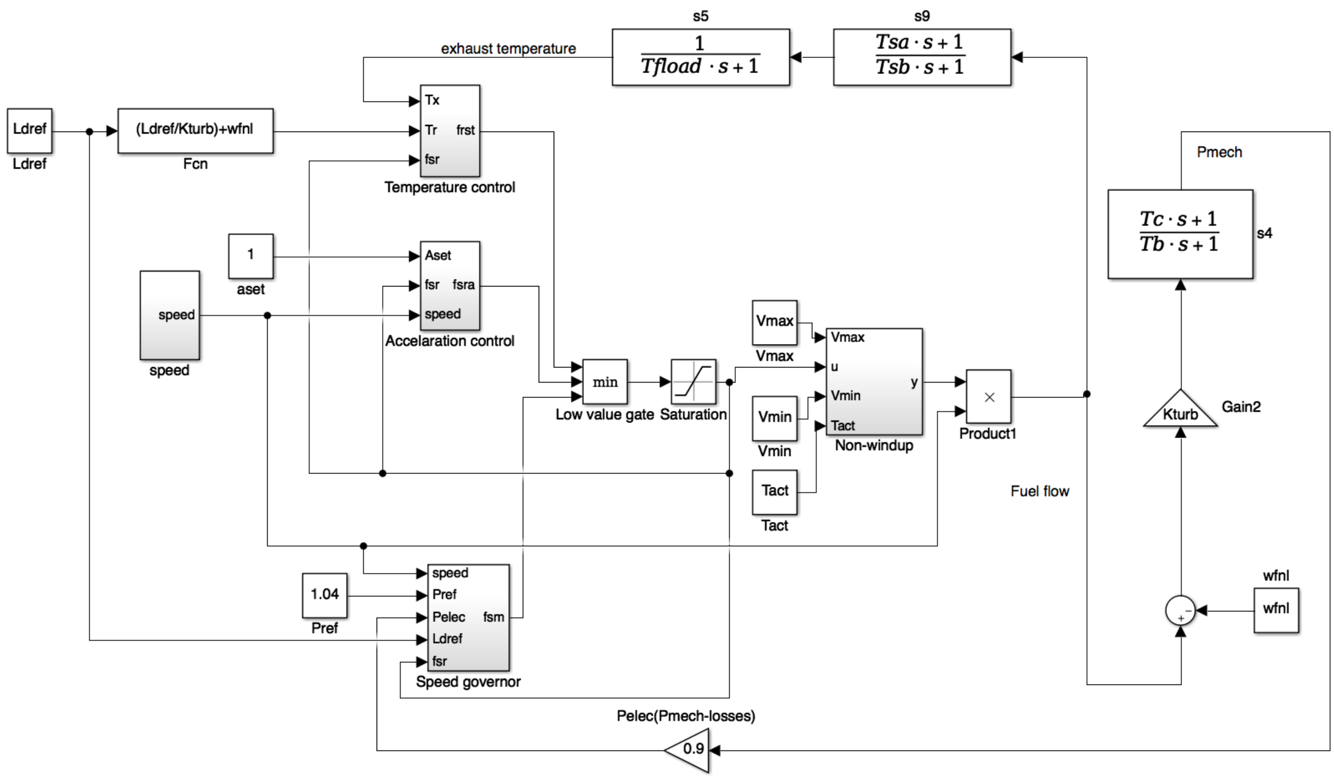

Figure 3.2: Implementation of the GGOV1 model in Simulink

The turbine-governor model is used for determining the mechanical power of the shaft (Pmech). In this implementation, the load control block in Figure 3.1 is set to limit a maximum output of exhaust temperature, so called temperature control here. Tfload represents the time constant in the measurement of temperature. In the temperature control, T_r-T_x represents the exhausted temperature error followed by the proportional controller with gain(Kpload). The PI controller

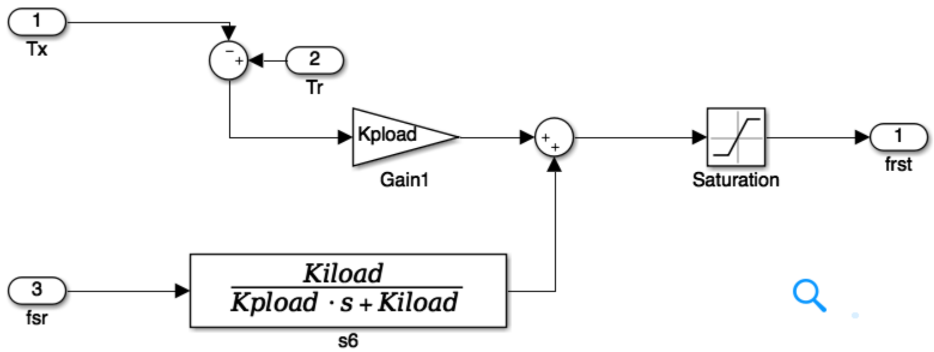

Figure 3.3: GGOV1 temperature control

with Kpload and Kiload accounts for the "fsr"(governor output which represents the fuel flow command determined by the lowest level of fsrt, fsra, and fsrn), which represents the feedback for tracking logic here.

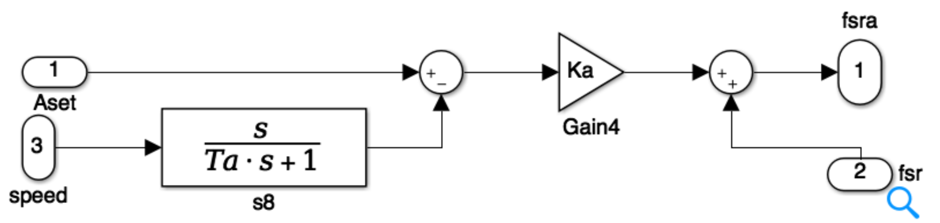

Figure 3.4: GGOV1 acceleration control

The acceleration controller, which is required for startup of the gas turbine. The acceleration control used in GGOV1 with a proportional controller with gain Ka is implemented in Figure 3.4. The setpoint(Aset) of the acceleration limiter can disable the control when gets large enough. The s8 block with time constant(Ta) taking the derivative of speed works as a filter to remove the noise amplified during this process.

When speed decreases, the electrical power will be changing. At the speed governor section, the negative feedback of electrical power (Pelec) will be also changing. We can see that in the above model, the loop speed governor incorporated with PID controller brings the system back to steady state.

The speed governor implemented in Figure 3.5 includes a fsrn regulator where a PID controller is implemented as shown in Figure 3.6. The proportional, integral and derivative controller with

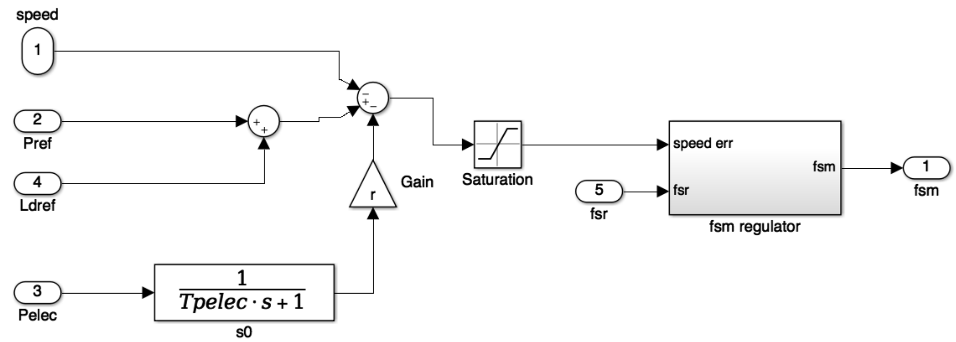

Figure 3.5: GGOV1 speed governor

coefficient Kpgov, Kdgov and Tdgov balance the speed error, and the Kigov/Kpgov controller works with feedback of the signal fsr(the fuel flow command the minimal among the outputs of the three controllers) provided as an input for the tracking logic.

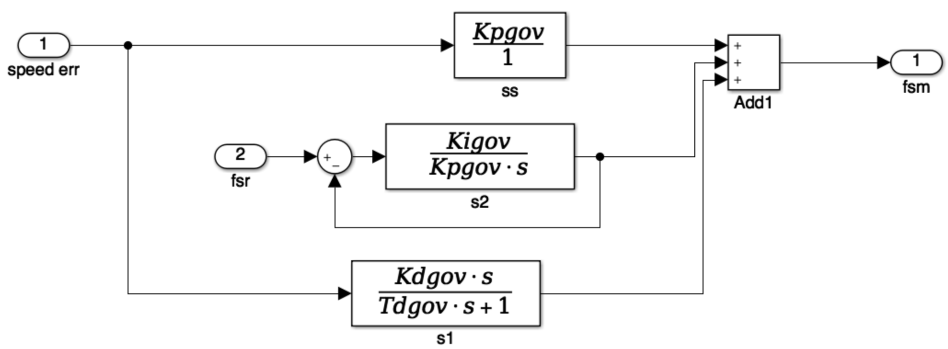

Figure 3.6: GGOV1 fsrn regulator

The non-windup block developed in last chapter was utilized in the GGOV1 model as well to prevent the windup. In this system, the fuel flow was determined by the fuel flow command "fsr" influenced by both valve position and speed. The valve changing rate limit is included in this block right before the integrator.

In the GGOV1 model, when the speed is changing as in Figure 3.8, fuel flow and Pmech react as shown in Figure 3.9 and Figure 3.10.

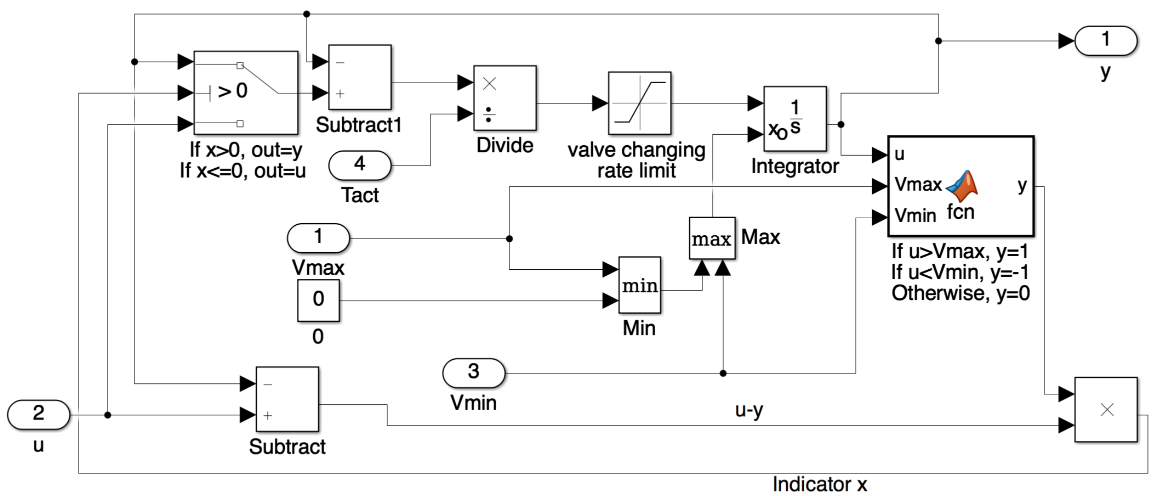

Figure 3.7: GGOV1 non-windup subsystem

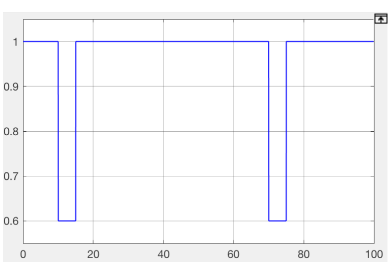

Figure 3.8: GGOV1 speed

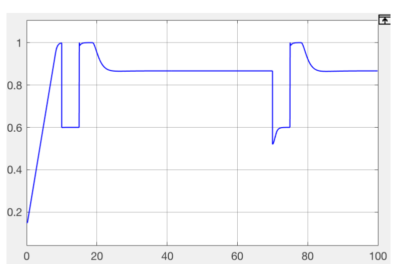

Figure 3.9: GGOV1 fuel flow

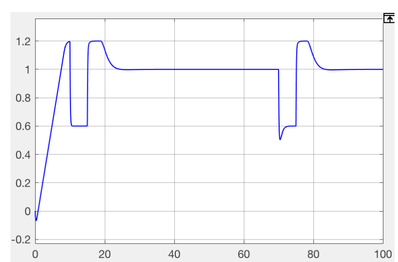

Figure 3.10: GGOV1 Pmech

Parameter	Representation	Value
R	Governor Droop	0.04
Tpelec	Electrical power transducer time constant	1
Maxerr	Maximum value for speed error signal	0.05
Minerr	Minimum value for speed error signal	-0.05
Kpgov	Gov. proportional gain	10
Kigov	Gov. integral gain	2
Kdgov	Gov. derivative gain	0
Tdgov	Gov. derivative controller time constant	1
Vmax	Maximum valve position limit	1
Vmin	Minimum valve position limit	0.15
Tact	Actuator time constant	0.5
Kturb	Turbine gain	1.5
wfnl	No load fuel flow	0.2
Tb	Turbine lag time constant	0.1
Tc	Turbine lead time constant	0
Tfload	Load Limiter time constant	3
Kpload	Load limiter proportional gain for PI controller	2
Kiload	Load limiter integral gain for PI controller	0.67
Ldref	Load limiter reference value	1
Ropen	Maximum valve opening rate	0.1
Rclose	Maximum valve closing rate	-0.1
Aset	Acceleration limiter setpoint	0.01
Ka	Acceleration limiter gain	10
Ta	Acceleration limiter time constant	0.1
Tsa	Temperature detection lead time constant	4
Tsb	Temperature detection lag time constant	5

Table 3.1: GGOV1 Parameter as described in [4]

Chapter 4

Two-Area System Models

In the real world, in a grid there are several generators and associated control systems. A combination of plants can meet dynamic load more economical.

In this section, two kinds of two-area systems will be introduced and implemented. The fuel flows of each generator and the power flow between two areas will be presented, respectively.

The basic idea of two-area system can be represented by these picture below.

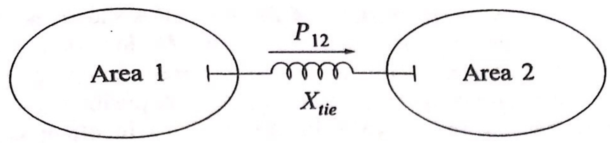

Figure 4.1: Two-area system[7]

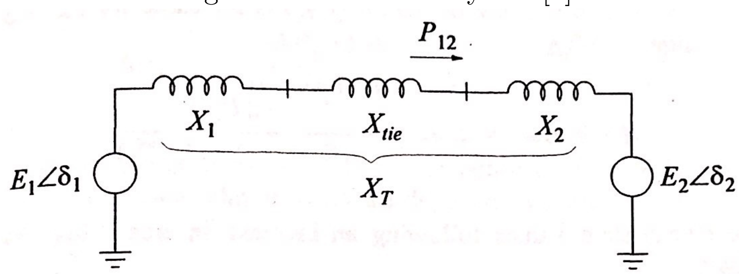

Figure 4.2: Two-area system electrical equivalent[7]

The two areas are connected and there is power flow between them. Thus, there may be a tertiary control to be designed in this system.

4.1 Two-Area System With Only Primary Speed Control

The simplified block diagram is shown in Figure 4.3.

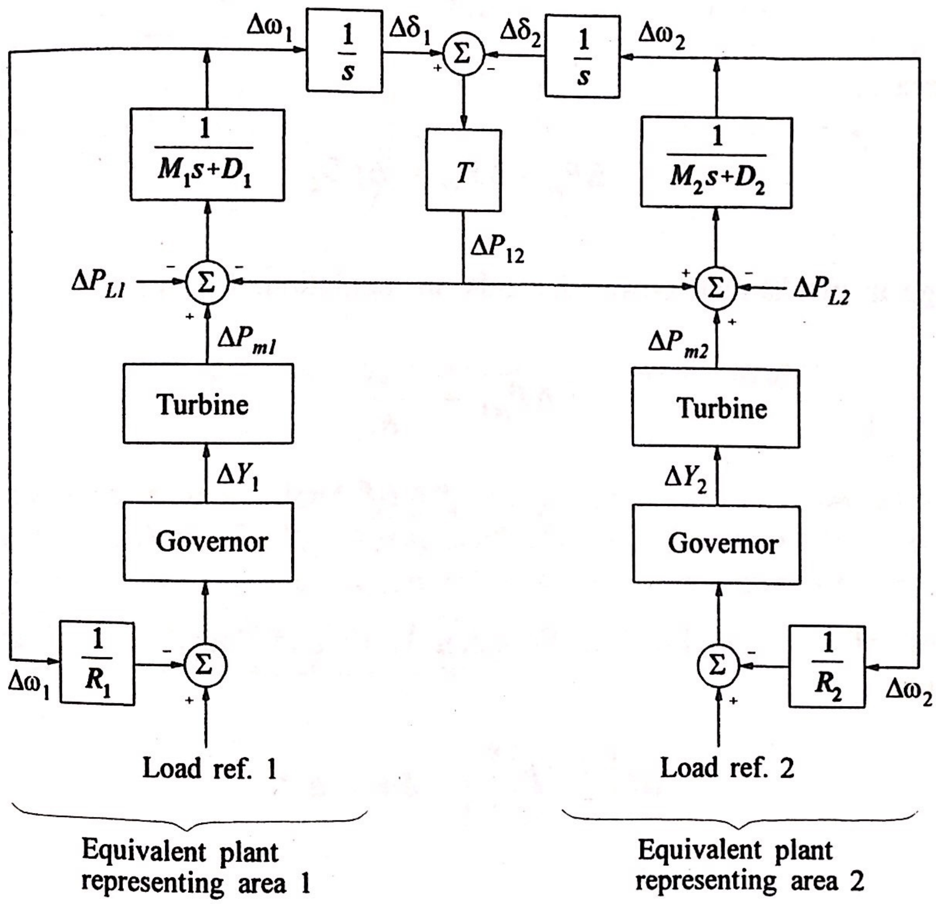

Figure 4.3: Two-Area System With Speed Control [7], page 603

In this block diagram above, ΔP_{12} represents the power flow from area1 to area 2, ΔP_{L1} and ΔP_{L2} represent the power demand(Pelec) of two areas. ΔP_{m1} and ΔP_{m2} represent the mechanical power(Pmech) of two areas. $\Delta\omega_1$ and $\Delta\omega_2$ represent the angular velocities, $\Delta\delta_1$ and $\Delta\delta_2$ represent the angular displacements. T is the synchronizing torque coefficient.

In the block diagram shown in Figure 4.4, there are two identical GAST models linked with each other. There is a power flow from area 1 to area 2. In the implementation, the transfer function 1/(Ms+D) was represented by several blocks with the same function. In our implementation, we used the identical GAST models in each area, to see how it react when one of two areas is subject to a sudden change of power demand. The power demands in two areas are shown in Figure 4.5 and Figure 4.6:

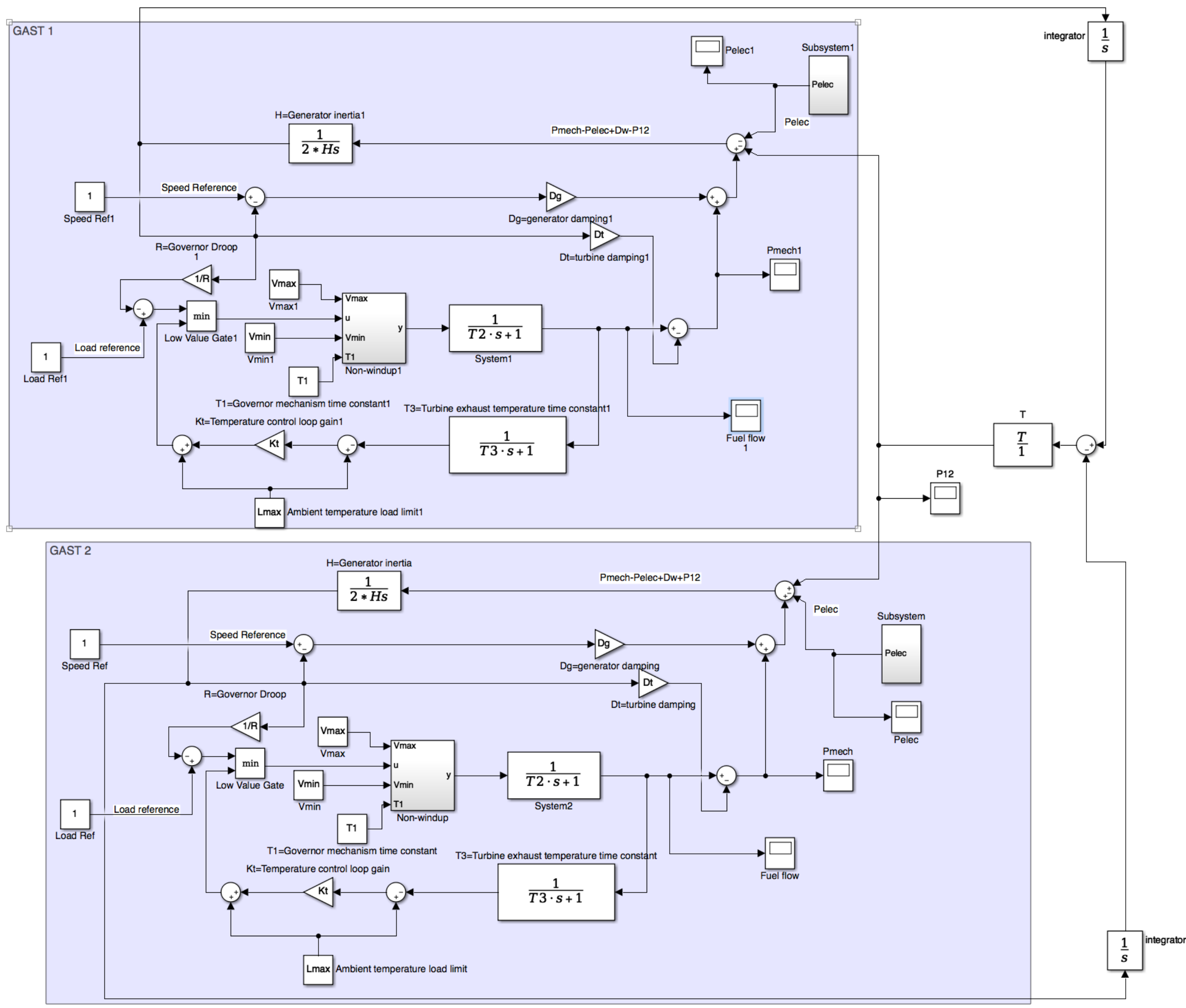

Figure 4.4: Implementation of Two-area system with speed control

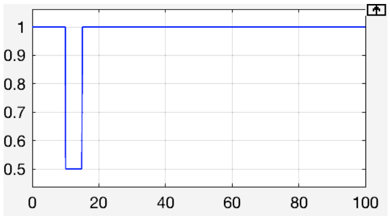

Figure 4.5: P_{L1}

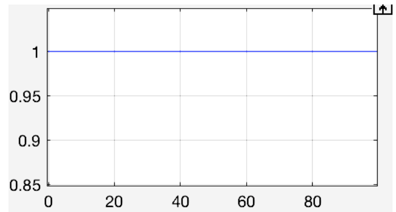

Figure 4.6: P_{L2}

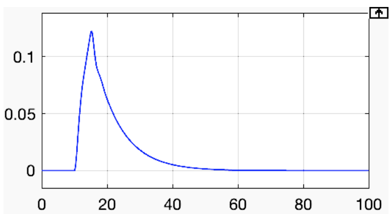

Figure 4.7: P_{12}

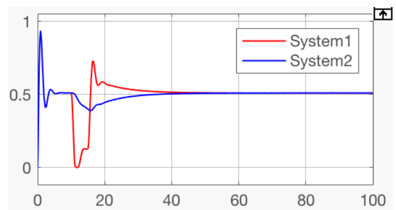

Figure 4.8: Fuel flow

From these Figure 4.5 and Figure 4.8, the initial blue spike may be an effect of initial conditions that are not properly initialized. The important part of the figure are the response starting at t=10s. When there is a suddenly drop demand in area1, the fuel flow in area 1 react immediately and the fuel flow in area 2 reacts more slowly.

4.2 Two-Area System With Supplementary Control

In this section a two-area system with supplementary control will be introduced and implemented. The basic objective of supplementary control is used to balance load and generation in case of large disturbance. In this system, the load control must maintain the frequency at the scheduled value. The simplified block diagram of two-area system with supplementary control is shown in Figure 4.9.

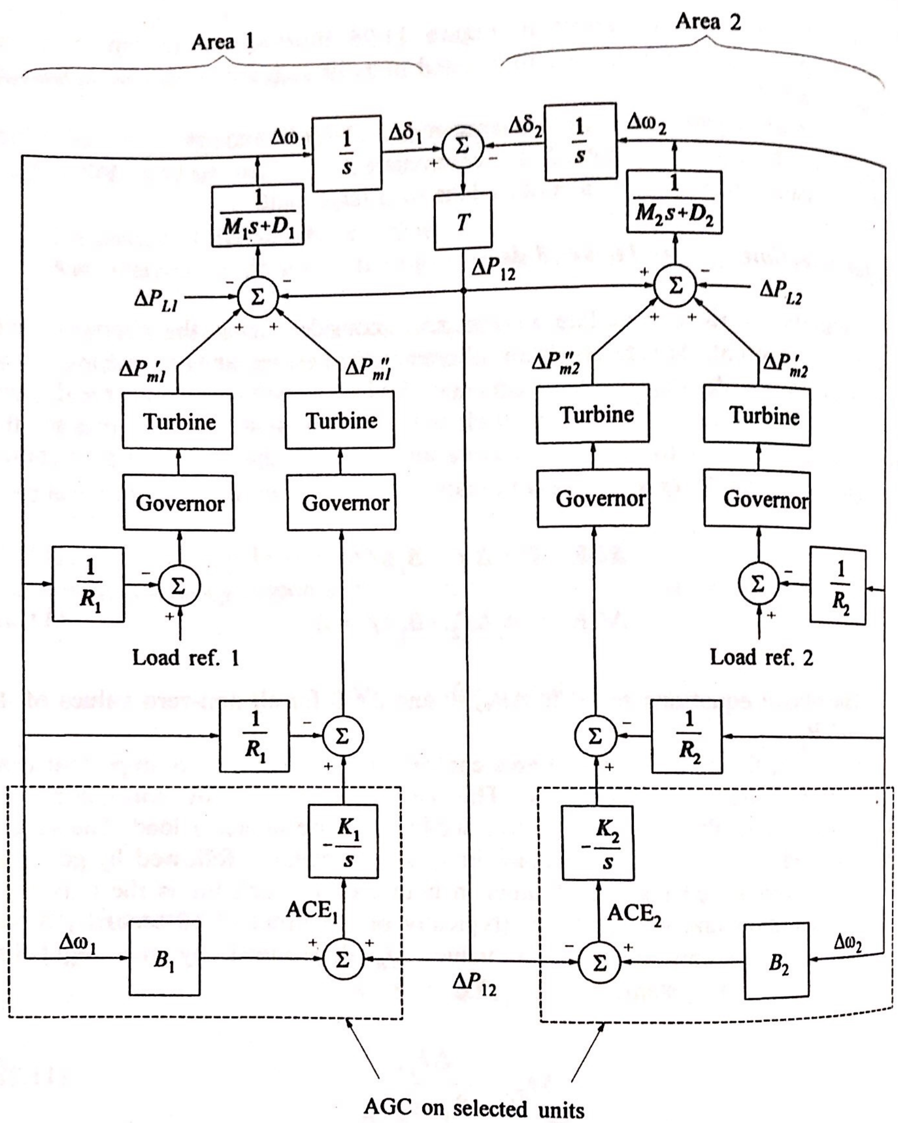

Figure 4.9: Two-Area System With Supplementary Control[7](page608)

In two-area system with supplementary control, only the area has disturbance should be set a supplementary control. The block diagram of the implementation is shown in Figure 4.10. In this implementation, the area 2 has no supplementary control block and three GAST models are set with different parameters.

As shown in Figure 4.11 and Figure 4.12, the electric power signal in area 1 has a disturbance, and the electric power signal in area 2 is stable. When this disturbance occurs, the turbine in area 1 will react immediately, then the turbine in area 2 reacts. We observe that the supplementary control does not seem to play a significant role in this test.

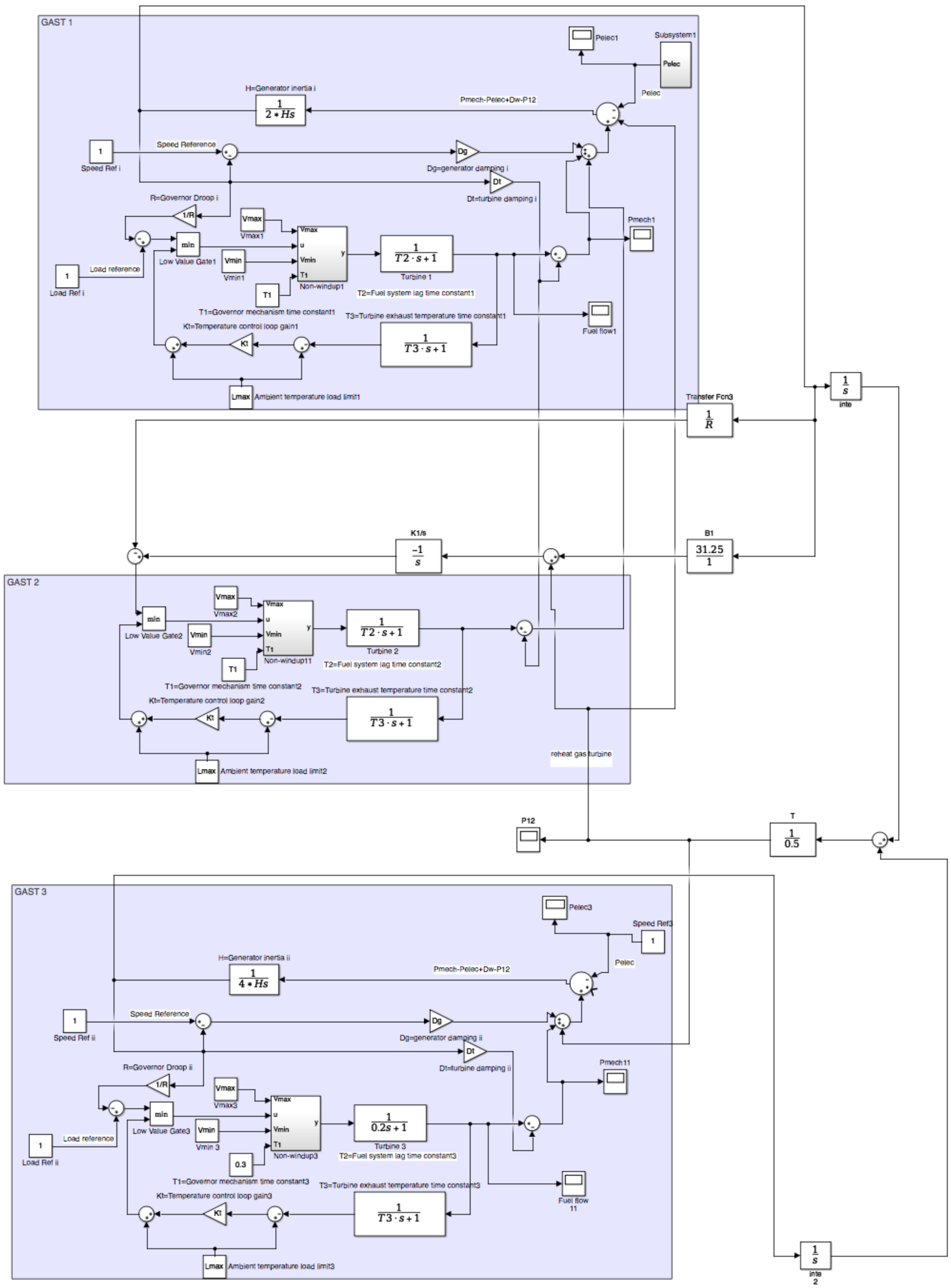

Figure 4.10: Two-Area System With Supplementary Control

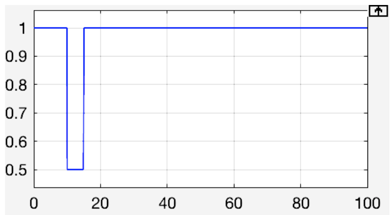

Figure 4.11: Input signal in area 1

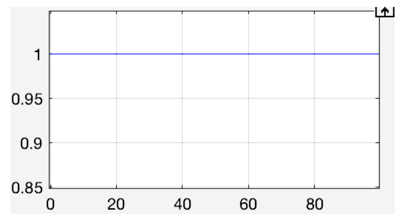

Figure 4.12: Input signal in area 2

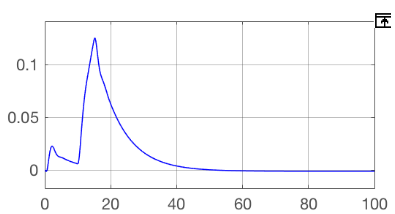

Figure 4.13: ΔP_{12}

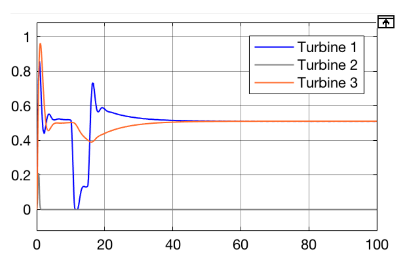

Figure 4.14: Fuel flow

Chapter 5

Summary and future work

In this thesis, we explore some of the key components in a turbine-governor model. Implementation of GAST model and GGOV1 model are studied in detail. In particular, we compare possible implementations for the non-windup blocks. During this study, the tuning of the PID controller caught my attention. The tuning can be considered as an optimization problem whose objective is minimizing the disturbance influence and the cost. Usually, tuning the PID gains insists in finding the best gains to minimize the error. The exploration to find the optimal gains of the PID controllers can be taken into account for future work.

Besides, in this thesis more complicated models including two-area system were also implemented. Usually in these hybrid system the turbine model which only contains governor and turbine was chosen for simplicity. Thus, the speed droop control can be represented by a single block. In our simulation the GAST model which already contains a droop control was used, therefore the speed droop control block was represented by several blocks with same function. Ideally, we should try to incorporate the GGOV1 model included in this system. One should represent the droop control and the supplementary control by blocks with the same function. In future work, we could try to include various controllers in the two-area model and measure their impact on system performance and control.

Bibliography

[1] NEPLAN AG. Turbine-governor models. 2015.

[2] Karl Johan Åström and Tore Hägglund. *PID controllers: theory, design, and tuning*, volume 2. Instrument society of America Research Triangle Park, NC, 1995.

[3] S Balamurugan, R Joseph Xavier, and A Ebenezer Jeyakumar. Application of genetic algorithm in optimal PID gain tuning for heavy duty gas turbine plant. *Journal of Electrical Systems*, 4(4), 2008.

[4] North American Electric Reliability Corporation. Gas turbine governor modeling. 2017.

[5] Puja Dash, Lalit Chandra Saikia, and Nidul Sinha. Automatic generation control of multi area thermal system using bat algorithm optimized PD–PID cascade controller. *International Journal of Electrical Power & Energy Systems*, 68:364–372, 2015.

[6] Mallipeddi Kavya and Gummadi Srinivasa Rao. Tuning of PID controller in an interconnected power system using particle swarm optimization. *International Journal of Computer Applications*, 118(16), 2015.

[7] Prabha Kundur. *Power system stability and control*, volume 7.

[8] Akhil S Menon, N Ramesh Babu, and Sreedhar Desabhatla. Study on the impact of turbine controls on transient stability of synchronous machine. *Journal of Green Engineering*, 6(2):1–22, 2016.

[9] M Nagpal, A Moshref, GK Morison, and P Kundur. Experience with testing and modeling of gas turbines. In *Power Engineering Society Winter Meeting, 2001. IEEE*, volume 2. IEEE, 2001.

[10] Les Pereira, John Undrill, Dmitry Kosterev, Donald Davies, and Shawn Patterson. A new thermal governor modeling approach in the WECC. *IEEE Transactions on Power Systems*, 18(2):819–829, 2003.

[11] Thang Diep Thanh, Quang Nguyen Phung, and Huy Nguyen Duc. Power flow analysis for islanded microgrid in hierarchical structure of control system using optimal control theory. *Journal of Electrical Systems*, 13(4), 2017.

Biography

Qinxu Gu was born in 1994 in China. She graduated from Tianjin University with a Bachelor of Engineering in Logistics Engineering in June 2016. And she is now attending Lehigh University for her graduate education. She was highly interested in the fields like mathematics and algorithms. She is grateful that Industrial Systems Engineering department gave her knowledge and courage to explore these fields. She is now completing a Master of Science degree in Industrial Systems Engineering, and is expected to graduate in May 2018.